ENGINEERING SYSTEMS

DOI 10.15826/rjcst.2016.1.002 УДК 697.1

De Rosa M.[1], *Bianco V.*[2], *Scarpa F.*[3], *Tagliafico L. A.*[4]
[1–4] University of Genoa,
Genoa, Italy
E-mail: [2] *vincenzo.bianco@unige.it*

MODELLING OF ENERGY CONSUMPTION IN BUILDINGS: AN ASSESSMENT OF STATIC AND DYNAMIC MODELS

Abstract. The aim of the present paper is to show recent results obtained in modeling the building system, presenting a review on the common numerical models used to estimate the energy consumptions. In particular, both steady-state and dynamic models are investigated by analyzing their main assumptions, limitations and fields of usage. As a matter of fact, the most common models are based on steady state approaches, but new technologies and the need to implement innovative regulation criteria for heating and cooling systems by performing detailed coupled studies on the building and heating/cooling systems, push towards the use of dynamic tools with low computational costs. Therefore, the use of dynamic models is often suggested, especially when different building configurations are investigated (as e. g. in the design stage or for a renovation perspective). Starting from this point, sensitive analyses on the installation of a proper insulation in the building envelope is then presented.

Keywords: energy demand, building, wall modeling, energy efficiency, degree days.

Де Роса М.[1], *Бьянко В.*[2], *Скарпа Ф.*[3], *Тальяфико Л. А.*[4]
[1–4] Университет Генуи,
Генуя, Италия
E-mail: [2]*vincenzo.bianco@unige.it*

МОДЕЛИРОВАНИЕ ЭНЕРГОПОТРЕБЛЕНИЯ ЗДАНИЙ: ОЦЕНКА СТАТИЧЕСКОЙ И ДИНАМИЧЕСКОЙ МОДЕЛЕЙ

Аннотация. Цель данной работы — показать последние результаты, полученные при моделировании системы здания, с описанием общих численных моделей, используемых для оценки энергопотребления. В частности на статических и динамических моделях исследованы основные допущения, ограничения и область использования путем их анализа. Собственно говоря, наиболее распространенные модели основаны на установившихся подходах, но новые технологии и необходимость внедрения для систем отопления и холодоснабжения инновационных критериев регулирования с использованием подробного анализа здания и систем отопления/охлаждения, подталкивают к использованию динамических инструментов с низкими вычислительными затратами. Таким образом, часто целесообразно использование динамических моделей, особенно когда существуют разные конфигурации здания (как, например, в стадии проектирования или для перспективной реконструкции). В статье представлен анализ установки правильного утеплителя в ограждающих конструкциях.

Ключевые слова: энергопотребление, здание, модель стен, энергоэффективность, отопительный период.

Nomenclature

a, b	Forced convection coefficient
C	Thermal capacitance or Heat capacity ($J \cdot K^{-1}$)
C_t	Natural convection coefficient ($W\,m^{-2}\,K^{-4/3}$)
CDD	Cooling degree-days (°C)
CDD*	Modified cooling degree-days (°C)
H	global building transmission coefficient [$W\,K^{-1}$]
HDD	Heating degree-days (°C)
$I_{0,y}$	Total horizontal solar radiation in the year computed by CDD* model ($W\,m^{-2}$)
$\dot{q}$	Heat flux (W)
R	Thermal resistance ($K\,W^{-1}$)
S	Surface (m^2)
t	Time (s, h)
T	Temperature (°C)
V	Volume (m^3)

Greek letters

α	Solar height angle/absorbance coefficient
β	Surface tilt angle (°)
γ	Surface azimuth (°)

δ Declination angle (°)
δT_m difference between base and monthly mean temperature [°C]
χ Parameters for CDD* calculation
θ Incidence angle between solar radiation and surface normal axis (°)
σ standard deviation
φ latitude [deg]
η efficiency
ω Hour angle (°)

Subscripts

b Base temperature
conv Convection
cs Cooling system
d Days
e External
h Hour
hs Heating system
i Internal
is Internal sources
irr Radiation
j Wall index for vertical walls and roof
m month
s Solar
sg Solar gain
v Ventilation
t Total
v Ventilation
w Wall
win Windows
y Year

1. Introduction

The global increase of energy demand has assumed a paramount importance concerning the reduction of the CO_2 emissions and to mitigate the climate change. Moreover, the growing trend in energy demand causes a relevant issue on introducing correcting energy policies in all sectors. In this context, buildings are responsible of about 40 % of the total energy consumption in Europe, with a major quote of 25 % due to households, representing the largest sector in all end-users area [1]. More in detail, energy in households is consumed for different purposes — such as hot water, cooking and appliances — but the dominant end-use is represented by space heating, which is generally responsible for around 70 % of total consumption in households.

This topic represents a crucial issue, especially considering the expected increase of the energy demand in the building sector, mainly due to the increasing consumptions of developing countries and to climate changes. A lot of studies have been conducted in order to quantify the impact of the climate change on the building consumptions. Generally, a double effect is expected [2]: (i) a decrease of the global heating energy demand by over a 30 % and, on the other hand, (ii) an increase of the cooling energy demand by about 70 %.

For this reason, the building sector has gained a relevant attention in the scientific community in order to implement mitigation measures in order to increase energy efficiency regarding all the possible aspects of the building design (envelope, internal condition, heating/cooling systems, renewable energies, etc.), as reported in Wan et al. [3]. To this aim the 91/2002 "Buildings Energy Performance Directive" [4] was emanated to introduce several requirements for new and existing buildings in EU.

Generally, to achieve this goal, a correct and optimized design is required and, therefore, the utilization of effective decision making tools is mandatory. These tools allow estimating the future energy demand and the parameters that affect the consumptions, in order to minimize the energy intensity. As a matter of fact, the estimation of the total building consumptions (mainly for heating and cooling purposes) permits mainly (i) to perform energetic assessment with maintenance and renovation aims for existing buildings and (ii) to outline the main design characteristics for new buildings. Moreover, in a larger perspective, it is possible to define scenario analyses in regional and national scales in order to detect the most suitable measures which guarantee the greater energy saving.

In this context, software able to predict the heating and cooling energy demand represents useful tools to perform parametric analyses with the aim to detect the best solution to enhance energy efficiency. The most common models are based on steady state approaches, such as the degree-days method [5] and the common standards [6–7]. These methods are usually used to perform preliminary energetic assessments, essentially related to the renovation of existent buildings, and to preliminary design stage for new constructions, thanks to their fast calculations. On the other hand, new technologies which exploit the building thermal inertia, such as free cooling [8] or phase change materials [9], require transient thermal analyses, which result fundamental in order to propose optimal energy saving solutions and to develop optimized control criteria. These issues are important especially for systems in which more energy sources are coupled together (such as SAHP, GHPS, PV/T-SAHP, etc.) making a sort of integrated system for which short time regulation rules assume an important role in the global energy performance [10]. Moreover, transient approach results to be essential for analyzing new construction materials which tend to delay the fluctuations of the external climatic conditions.

In order to build transient numerical tools, several dynamic approaches have been developed and tested over the last years, most of them implemented on commercial tools, such as TRNYS and EnergyPlus. Moreover, the increase of computer performances permits the use of mathematical packages, such as Matlab/Simulink, to create in-house custom adaptable tools for evaluating the building energy demand with a relative low strength and without excessive computational costs. A recent development in these directions was performed at University of Genoa (Italy) by developing a simplified dynamic tool, called BEPS (Building Energy Performance Simulator) [11]. This tool, based on the Matlab/Simulink Environment, implements a dynamic numerical model which permits accurate results and fast calculation at the same time, allowing a high level of customization in terms of building and heating/cooling systems designs. The model validation, described in [11] and based on the comparison between BEPS results with ones obtained by consolidated commercial codes, showed that BEPS is able to predict the heating and cooling energy demand for all benchmark buildings in all tested climatic conditions.

Starting from the above considerations, the present paper summarizes the recent results obtained in modeling the building system, presenting a review on the common numerical models used to estimate the energy consumptions. In particular, both steady-state and dynamic models are investigated analyzing their main assumptions, limitations and field of usage. Finally, a parametric investigation which shows how these models can be used in an energy saving perspective is also presented.

2. Steady state modelling

Steady state approaches permit to perform fast calculations neglecting the dynamic effects and assuming averaged climatic data. In this context, the simplest steady-state model is represented by the degree days (DDs) method [5]. Generally, degree days are important climatic parameters which have their origin in agricultural research and nowadays they are used in a lot of fields (energy, architecture, agriculture, entomology, etc.). Essentially, they are based on the idea to capture the variations of the outdoor temperature, in terms of amplitude and frequency, with respect to a reference temperature (also called "base temperature" T_b, which consists of in the nominal comfort condition temperature for building application). For heating calculations, the degree days is a sort of accumulated temperature which measures the extent and the duration for which outside temperature is lower (greater in cooling cases) then the base temperature [12], as shown in Fig. 1. In the following section, the main calculation methods and uses of DD are explained.

2.1. Notes on degree days calculation techniques

Several methods can be adopted to calculate degree-days depending on the availability of climatic data of the specific location, due to the limitations of the available external temperature data. The mean daily degree-hours represents the most accurate way to determine the yearly heating (HDD) and cooling (CDD) degree days and they are defined as the average of the daily degree hours, as shown in Eq. 1 for heating and Eq. 2 for cooling.

$$HDD_t = \sum_{d=1}^{D_t} \left(\frac{1}{24} \sum_{h=1}^{24} \left(T_{b,hs} - T_{e,h} \right)^+ \right)_d \tag{1}$$

$$CDD_t = \sum_{d=1}^{D_t} \left(\frac{1}{24} \sum_{h=1}^{24} \left(T_{e,h} - T_{b,cs} \right)^+ \right)_d \tag{2}$$

Since hourly profiles of external temperature are not available for any locations, reduced climatic dataset can be used for calculating HDD and CDD using other simplified methods based on daily mean temperature, defined as in Eq. 3. The ASHRAE [13] calculation method (Eq. 4) is one of the most common permitting a significant reduction of data due to the fact that it requires only the maximum and minimum temperatures of each day. The main limitation is due to the neglecting also the days in which minimum daily temperature is however below the base temperature and a heat flow can occur for a portion of the day. In order to overcome this issue, by the UK Meteorological Office (UKMO) approach [5], shown in Eq. 5, introduces several relationships to take into account the asymmetry between the daily mean temperature (Eq. 3) and the diurnal temperature variations (in Eq. 5, $\Delta T_{max} = T_{max} - T_b$ and $\Delta T_{min} = T_b - T_{min}$).

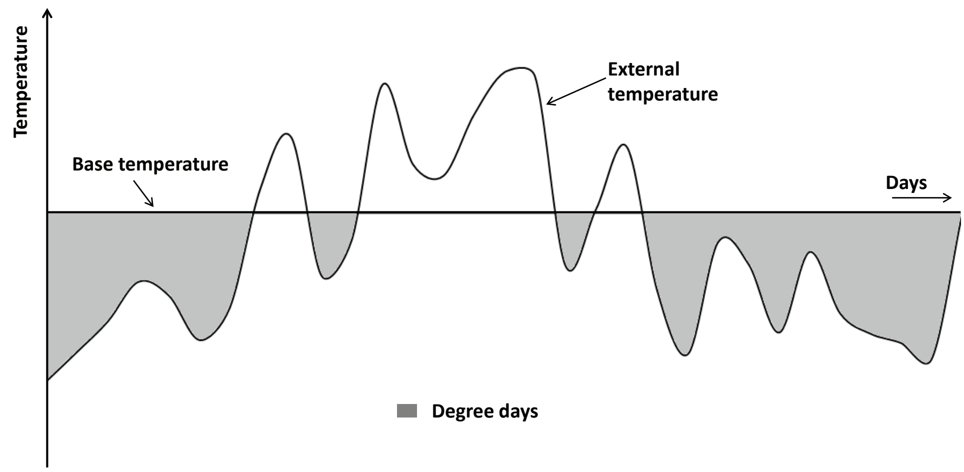

Fig. 1. Definition of heating degree days

$$\bar{T}_{e,d} = \left(T_{\max} + T_{\min}\right)/2 \tag{3}$$

$$HDD_{y,ASHRAE} = \sum_{d=1}^{D_t}\left(T_{b,hs} - \bar{T}_{e,d}\right)_d^{+} \tag{4}$$

$$HDD_{y,UKMO} = \sum_{d=1}^{D_t}\begin{cases} T_{b,h} - \bar{T}_{e,d} & T_{\max,d} \le T_{b,h} \\ 0.5\cdot\Delta T_{\min,d} - 0.25\cdot\Delta T_{\max,d} & T_{\min,d} < T_{b,h} \text{ and } \Delta T_{\max,d} < \Delta T_{\min,d} \\ 0.25\cdot\Delta T_{\min,d} & T_{\max,d} > T_{b,h} \text{ and } \Delta T_{\max,d} > \Delta T_{\min,d} \\ 0 & T_{\min,d} \ge T_{b,h} \end{cases} \tag{5}$$

In order to reduce yet the climatic dataset, other methods are based on the monthly mean temperature and on the standard deviation σ. The most famous are Hitchin method [14] (Eq. 6, where the term ΔT_m is $\left(T_b - \bar{T}_m\right)$ and N_m represents the number of days in the month) and Schoenau and Kehrig method [15] (Eq. 7). The functions $f\,(Z)$ and $F\,(Z)$ are the normal (Gaussian) probability density function with mean 0 and standard deviation equal to 1 and the cumulative normal probability function, respectively.

$$DD_{m,HITCHIN} = \frac{N_m \Delta T_m}{1 - \exp\left[-\dfrac{2.5}{\sigma_m}\Delta T_m\right]} \tag{6}$$

$$DD_{m,SK} = N_m \sigma_d \left[\Delta T_m \cdot F\left(\Delta T_m\right) + f\left(\Delta T_m\right)\right] \tag{7}$$

Obviously, if the daily standard deviations σ_m are not tabulated, it is necessary to use the daily averaged temperature to calculate it, limiting the lower dataset purpose of these methods.

A recent comparison of the different methods were performed in [16], where external temperature profiles recorded in 2013 in Genoa (Italy) have been used. The analysis was conducted calculating the monthly HDD using different base temperatures and the results were presented in terms of percentage difference δ between the MDDH values and the other methods (Fig. 2). As highlighted in the paper, when consistent differences between external and the reference temperatures occur (high values of ΔT_m) all models are able to predict HDD values. On the other hand, if reference temperature is close to external temperature, the use of reduced dataset methods is not suggested.

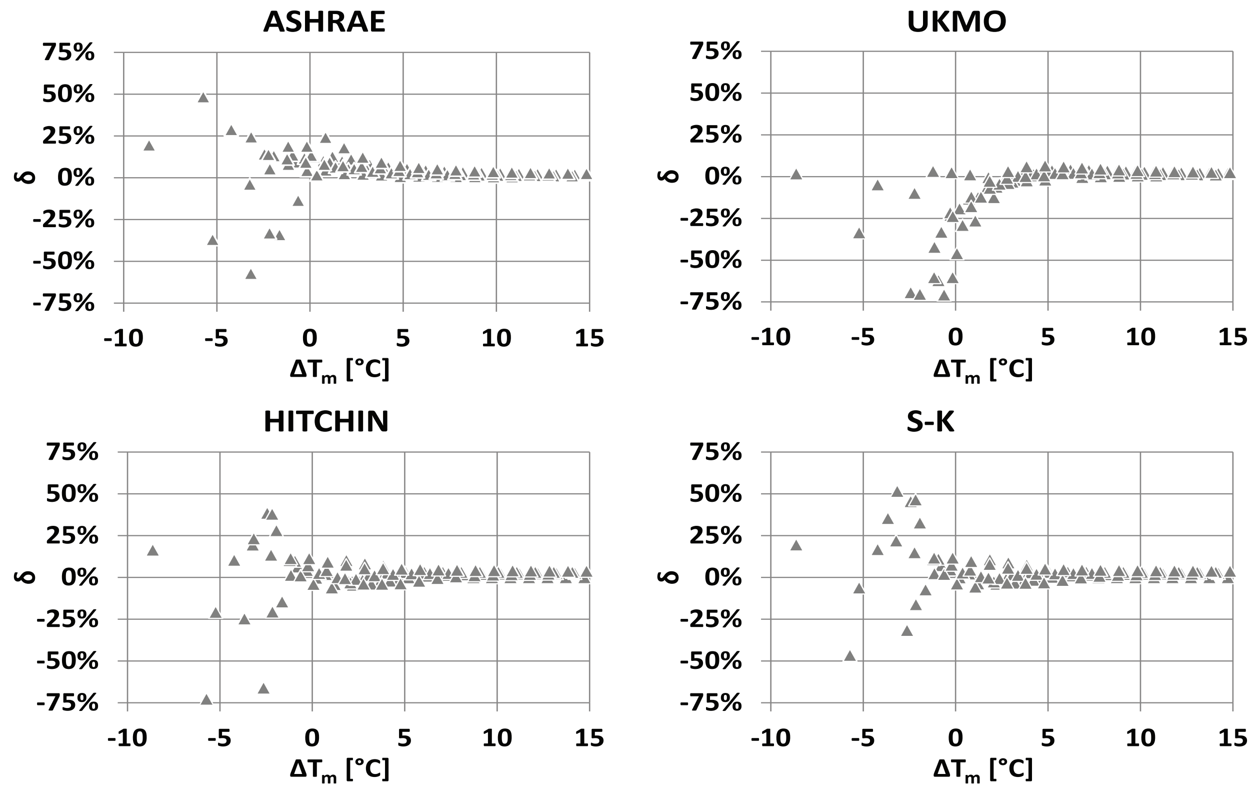

Fig. 2. Percentage difference trends of the approximate models against ΔT_m for HDD in Genoa [16]

2.2. The use of DD in building applications

The use of degree-days for heating energy consumption in buildings starts from 1934 [17]. Over the last few years, a lot of works have been performed in order to formalize their use in the prediction of energy demand of buildings, to quantify their values for different countries and their calculation uncertainties.

As already said, the importance of the DDs approach lies in their capability to perform fast analyses — in various fields and with different purposes. Generally, in building applications, the main purposes include (for a detailed review of works involving DDs can be found in [16]):

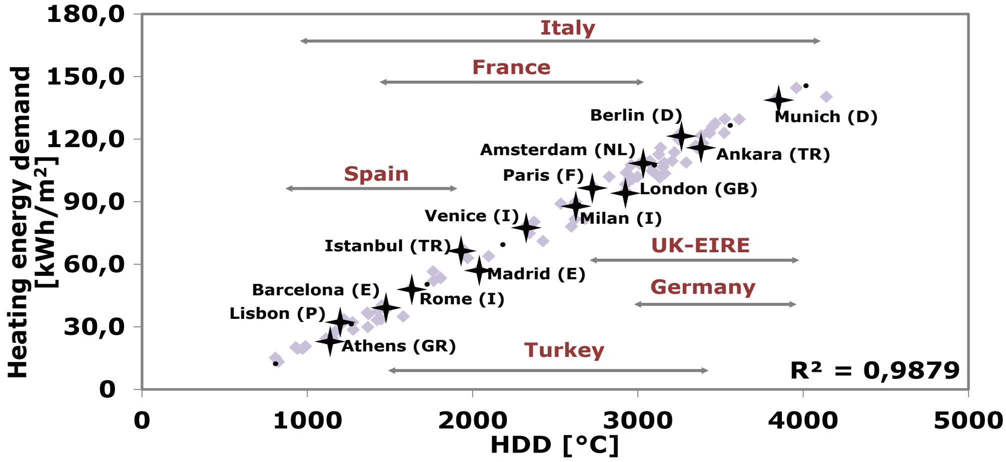

Fig. 3. Specific yearly heating energy demand of the benchmark building as a function of the HDD (T_b = 20 °C)

— the energetic assessment for maintenance and renewal of existent buildings;

— to perform energetic performance analyses for new constructions in the preliminary design stage;

— to conduct analyses on the regional energy consumption considering the existent building stocks, — the heating/cooling system typologies and the demographic distribution;

— the construction of scenario analyses for energy consumption forecasting, considering also the economic issued, to detect the most suitable policy measures in order to guarantee the highest energy saving.

The simplicity of this technique can be seen considering that in steady-state conditions the heat losses are directly proportional to the difference between internal and external temperature. Therefore, the yearly energy consumption E_y can be calculated as in Eq. 8, where: H (in W/K) is a global building transmission coefficient, t_h is the total heating/cooling time in a day (which can be assumed equal to 24h if a continuous heating/cooling is provided), $\eta_{hs/cs}$ is the efficiency of the equipment and DD_m is the yearly total heating (or cooling) degree days.

$$E_y = \frac{H \cdot DD_m \cdot t_h}{\eta_{hs/cs}} \qquad (8)$$

The importance of this definition is clear: considering a building and heating system for which the main characteristics (mainly, H, $\eta_{hs/cs}$ and t_h) are known, it is possible to determine (in a preliminary way) the total energy consumption for heating by calculating the total degree days of the specific locality (see section 2.1. for the main calculation techniques). The main assumption is that the energy consumption is mainly driven by the temperature difference between the internal set point temperature (base temperature) and the external one. In other words, we assume the linearity of the energy consumption against this difference, as it can be noted in Eq. 1, considering negligible the inertial effects. This assumption can be demonstrated observing Fig. 3 which reports the distribution against HDD of the heating energy consumptions obtained by using a numerical tool called BEPS [11] implementing a dynamic numerical model (see section 3). In particular, several simulations have been conducted considering the a benchmark building in different climatic conditions, demonstrating that the heating energy consumption can be easily correlated to HDD using a simple linear equation in which the coefficients depend on the building characteristics.

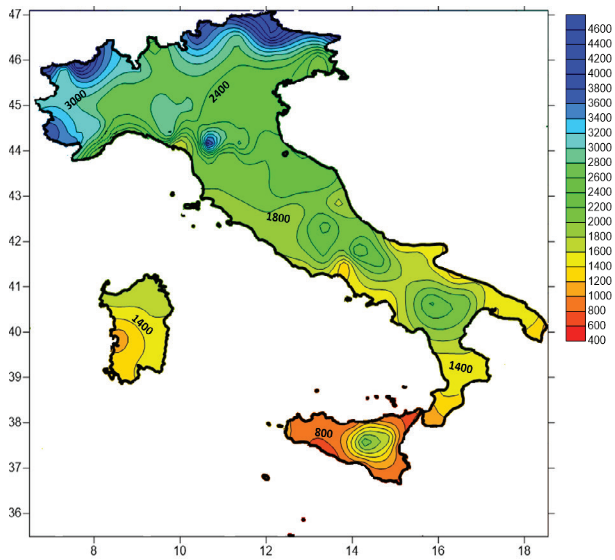

Fig. 4. HDD map for Italy (T_b = 20 °C) [16]

Another interesting aspect highlighted by Fig. 3 is represented by the wide range of HDD which are typical in Italy, as also shown in Fig. 4, due to its morphology which covers all the climatic conditions occurring in Europe. As a result, it is a hard task to define a single plan of actions to improve energy efficiency all over the country and, indeed, it should be necessary to divide the whole territory into a relevant number of sub-plans, well-tuned to the requirements of each specific location.

Performing the same analyses in terms of cooling energy consumption leads to completely different results,

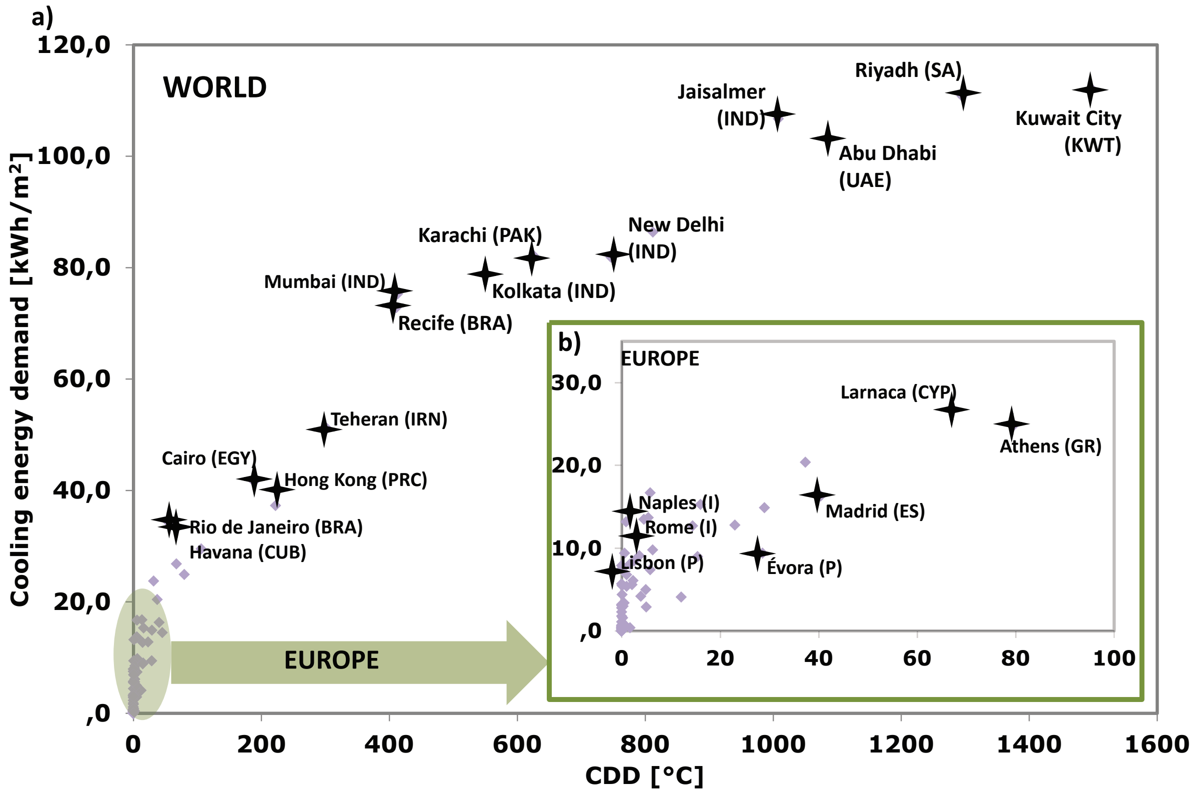

Fig. 5. Cooling energy demand trend against CDD: a) World, b) Augmented section for Europe cities

as shown in Fig. 5, where the energy consumption of a benchmark building (see next section for more details) is investigated in different climates. As it is possible to note, a scattered distribution occurs which tends to be decrease for greater CDD values (Fig. 5a) typical of locarions outside EU. On the other hand, Europe localities (Fig. 5b) present low CDD values (CDD < 150) for typical building applications and, in these conditions, the cooling energy demand is also affected by other phenomena, which are strictly related to the inertia of the building (e. g. solar irradiation, set point temperature, internal loads, etc.). As a consequence, the linearity assumption (and, more in general, the steady state hypothesis) cannot be considered valid in cooling calculation.

As demonstrated in [11], it is possible to restore the linearity assumption and, consequently, the validity of Eq. 2, by modifying the definition of standard CDD as follows:

$$\mathrm{CDD}_y^* = \mathrm{CDD}_y + \chi \cdot I_{0,y} \qquad (9)$$

where $I_{0,y}$ is the yearly horizontal solar irradiation of each locality, computed by summing the daily values only in the cooling period, while χ is the correction factor, which is adjusted in order to minimize the deviation of the linear regression. Fig. 6 shows the cooling energy consumption calculated by BEPS against the new CDD formulation (CDD*), demonstrating the validity of this approach.

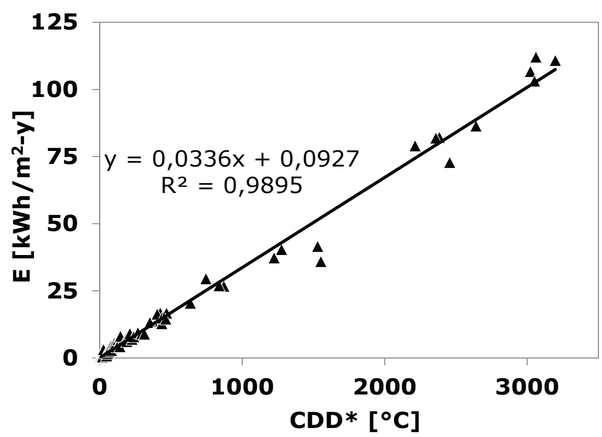

Fig. 6. Restored linearity trend of cooling energy demand using the new CDD* formulation [11]

2.3. Notes on the common standards for building energy assessment

The "Energy Performance of Building Directive" [18] and the "Energy Efficiency Directive" [19] are the main legislations on this topic in Europe. These directives introduce several requirements in order to reduce the energy consumption in buildings (e.g. all new buildings must be nearly zero energy buildings by 31 December 2020) by setting minimum energy performance requirements for new and existent buildings.

In this context, the ISO 13790:2008 [7] standard was introduced as calculation method to determine the annual energy use for space heating and cooling of residential or non-residential buildings. ISO 13790:2008 has been developed for buildings that are, or are assumed to be, heated and/or cooled for the thermal comfort of people, but can be used for other types of building or other types of use (e.g. industrial, agricultural, swimming pool), as long as appropriate input data are chosen and the impact of special physical conditions on the accuracy are taken into consideration.

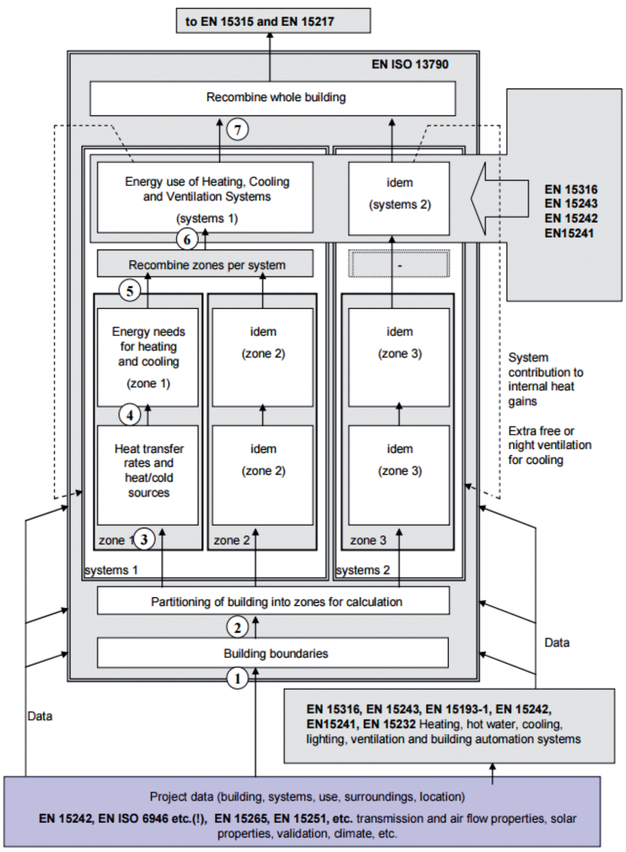

Fig. 7. Example of calculation steps suggested in ISO 13790:2008 [7]

The ISO 13790:2008 method, mainly based on steady-state approach and on the use of tables and charts for common configurations, includes the calculation of:

— the heat transfer by transmission and ventilation of the building zone when heated or cooled to constant internal temperature;

— the contribution of internal and solar heat gains to the building heat balance;

— the annual energy needs for heating and cooling, to maintain the specified set-point temperatures in the building.

It is important to state that ISO 13790:2008 describes a calculation procedure using a flexible structure and allowing the integration of other standards, which are often required for performing detailed calculations of particular systems (see Fig. 7). Due to the complexity of the whole structure, which cannot be easily reported in the present paper, we refer to the standard text for more details [7].

3. Dynamic modelling

In order to overcome the steady-state assumptions, several numerical models have been developed over the last years. The first attempt was made by Boyer et al. [20] who introduces the nodal analysis considering a one-dimensional conduction across the walls and introducing their thermal capacities. Nielsen [21] developed a simple tool to evaluate building energy demand in the early stages of building design. The equation system consists of two differential equations, one for the internal air and the second one for all the opaque structures grouped into a single effective capacitance. Moreover, an algebraic equation is added to account for the conduction across the walls and the solar contribution in the external surfaces.

Generally, the main requirements of a dynamic numerical model can be summarized as follows:

1. Detailed description of the building inertia (e.g. walls, internal environment, roof and floors).

2. Hourly climatic data the solar radiation, the external temperature and the wind conditions. In particular, for the last two climatic parameter, the orientations of the external wall surfaces are mandatory in order to compute correctly their contributes.

3. The number of equations should be determined balancing fast calculations with results accuracy. For this purpose, several simplifications of geometries and contributions are mandatory.

Thus, a simple numerical model can be developed starting from two main components: (i) the internal environment and (ii) the external walls. The internal environment corresponds to the total heated/cooled zone of the buildings in which the thermal comfort has to be preserved. This environment can be modeled as a single isothermal air volume with a unique thermal capacitance which has to be adjusted to take into account the inertia of furniture and internal walls (Fig. 8). This volume exchanges heat with the internal layer of the external walls and with the external air across the windows, while it receives heat by the internal free gain, due to persons and equipment, and solar radiation transmitted by the transparent surfaces. Considering all contributions, the transient energy balance equation for the internal air node can be written as follows:

$$C_i \frac{dT_i}{dt} = \dot{q}_{hs/cs} + \dot{q}_{is} + \dot{q}_v + \dot{q}_w + \dot{q}_{win} \tag{10}$$

where C_i and T_i represent the thermal capacitance and the note temperature. The main contributions are: the heating/cooling input thermal power ($\dot{q}_{hs/cs}$), the internal sources ($\dot{q}_{is}$), the heat transfer due to ventilation ($\dot{q}_v$), the heat transfer through all external walls ($\dot{q}_w$) and across the windows ($\dot{q}_{win}$).

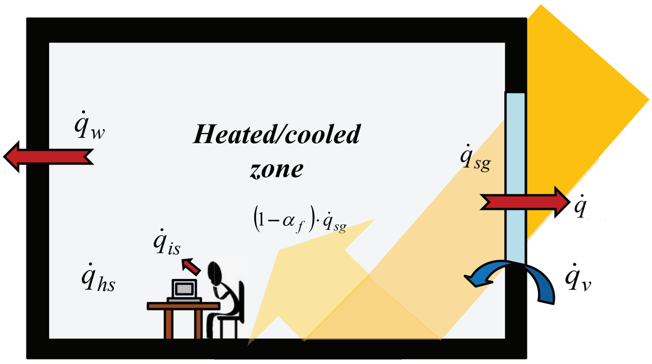

Fig. 8. Schema of the heat flows to whom the heated/cooled zone is subjected [11]

The external walls can be modeled adopting a lumped capacitance approach and using different discretization schema. The simplest approach consists of to consider two distinct layers (Fig. 9): (i) the internal one, which exchanges heat with the internal mass of air, and (ii) the external one, which is subjected to the combined effect of external air convection and solar irradiation. The wall thermal capacitance is lumped in a single temperature node which can be located according to the building internal characteristics. The energy balance equation of the opaque wall with orientation j can be written as in Eq. 11, where the terms $\dot{q}_{w/i,j}$ and $\dot{q}_{w/e,j}$ represent the heat fluxes between the wall node and the internal/external wall surfaces.

$$C_{w,j} \frac{dT_{w,j}}{dt} = \dot{q}_{w/i,j} + \dot{q}_{w/e,j} \tag{11}$$

The temperatures of the wall surfaces (mainly the external one) are affected by the input solar power and can be determined by considering two energy balances in steady state conditions (no thermal capacitance are considered for these nodes), as shown in Eq. 12 and Eq. 13.

$$\dot{q}_{w/i,j} + \dot{q}_{sg,j} = \dot{q}_{i,j} \tag{12}$$

$$\dot{q}_{w/e,j} + \dot{q}_{s,j} = \dot{q}_{e,j} \tag{13}$$

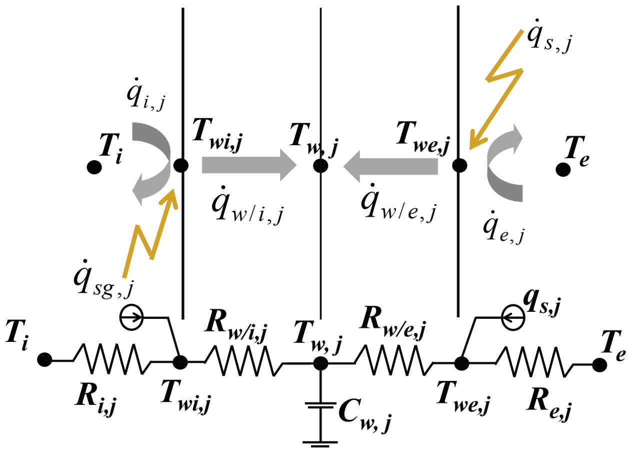

Fig. 9. Schema of the thermo-electrical approach for external wall modeling using two layers

In order to calculate the heat flow rate on the internal and external wall surfaces ($\dot{q}_{s,j}$ and $\dot{q}_{sg,j}$), the calculation of the internal and external convective heat transfer coefficients is required. Generally, the internal heat transfer coefficient, $h_{i,j}$, can be calculated considering only the natural convection term and assuming negligible the infrared irradiation between the internal surfaces.

The external heat transfer coefficient has to be calculated considering both radiation and convection terms according to the following equation [22]:

$$h_{tot,j} = h_{conv,j} + h_{irr,j} \tag{14}$$

$$h_{conv,j} = \sqrt{\left[C_t \left(\Delta T_j\right)^{\frac{1}{3}}\right]^2 + \left[aV^b\right]^2} \tag{15}$$

whereas the convection term h_{conv} can be estimated as shown in Eq. 15 [23,24], in which the first term represents the natural convection and the second one represents the forced convection due to wind speed. A detailed review of the different external convection algorithms used in buildings simulation is reported in [25].

In order to take into account the wind direction, each wall is classified thorough the definition of windward and leeward surface: a wall is considered as windward if the angle of incidence between the normal to the wall surface and the wind direction is less then ± 90° and leeward for all other directions [26].

3.1. Calculation of the solar radiation

The calculation of the solar radiation represents a main task when a detailed dynamic model has to be developed, considering its strong impact on the building dynamic behavior.

Generally, the solar radiation contribution on a wall external surface (such as $\dot{q}_{s,j}$ in the external wall energy balance) with orientation j can be calculated as shown in Eq. 16, where $\alpha_{w,j}$ is the surface absorbance coefficient while $I_{j,n}$ represents the global solar radiation normal to the wall, which can be calculated as shown in Eq. 17.

$$\dot{q}_{s,j} = \alpha_{w,j} S_{w,j} I_{j,n} \quad (16)$$

$$I_{j,n} = I_{b,n}\cos\theta_j + I_{d,n} + \left(I_{b,n}\sin\alpha + I_{d,h}\right)\cdot\xi_{r,w} \quad (17)$$

where:

$I_{b,n}$ = normal direct solar radiation [W m^{-2}];

$I_{d,h}$ = horizontal diffuse solar radiation [W m^{-2}];

$I_{d,n}$ is the sky diffuse solar radiation normal to the surface, which can be calculated according to Perez et al. [27].

The term $\xi_{r,w}$ represents the tilt solar redirected radiation factor, which can be calculated using the following equations:

$$\xi_{r,w} = \rho\frac{1-\cos\beta_j}{2} \quad (18)$$

In order to compute $I_{j,n}$, it is necessary to calculate the angle of incidence between solar radiation and wall surface normal axis θ_j (Eq. 19) and the solar height angle α (Eq. 20) at each time step.

$$\begin{aligned}\cos\theta_j &= \sin\delta\left(\sin\varphi\cos\beta_j - \cos\varphi\sin\beta_j\cos\gamma_j\right) + \\ &+ \cos\delta\left(\cos\varphi\cos\beta_j - \sin\varphi\sin\beta_j\cos\gamma_j\right)\cos\omega + \\ &+ \cos\delta\sin\beta_j\sin\gamma_j\sin\omega\end{aligned} \quad (19)$$

$$\sin\alpha = \sin\varphi\sin\delta + \cos\varphi\cos\delta\cos\omega \quad (20)$$

4. Discussion

In order to analyze the differences between steady state [7] and dynamic models (BEPS [11], TRNSYS and EnergyPlus), a standard building block of two floors with a total internal volume is 600 m^3 and a heated/cooled useful surface of 200 m^2 is assumed as benchmark. The window thermal transmittance is assumed equal to 2.465 W/(mK) for all components with a transmission coefficient is equal to 0.571. Moreover, two different wall structures are considered, heavy and light configurations, which differ by the thermal capacitance and the superficial mass of vertical walls. The main characteristics of the benchmark building are reported in Table 1 and Table 2.

To perform detailed dynamic simulations using BEPS, the hourly profiles of the following climatic variables are required:

— external temperature;

— normal direct radiation and diffused horizontal radiation, which allow to determine the total value of the total incident radiation on the surface;

— wind intensity and direction, necessary to determine the external convection coefficients for each surface.

Fig. 10 shows the comparison in terms of heating and cooling yearly energy demands between the steady state approach and dynamic models for three Italian cities with different climates: cold in Milan, moderate in Rome and warm in Palermo. As it is possible to note, the steady state approach results deviate from the more detailed models for both wall configurations. Therefore, the use of monthly averaged climatic data and neglecting the inertia effects (or using parameters to reproduce them) are not sufficient to predict correctly the yearly energy demand, especially in cooling seasons when these effects are stronger.

Table 1

Geometric data of the considered building [11]

Height	m	6
Base	m×m	10×10
Number of floors	-	2
Useful (heated/cooled) surface	m^2	200
Volume	m^3	600
Total dissipating surface	m^2	440
S/V	m^{-1}	0.73
Roof surface	m^2	100
Type of floor		on the ground
Vertical walls orientation		N-S-E-W
for each orientation		
Total Wall surface	m^2	60.00
Opaque surface	m^2	53.75
Windows surface	m^2	6.25

Table 2

Wall structure adopted in the present work [11]

Wall types		Transmittance	Specific thermal capacity
		W m^{-2} K^{-1}	kJ m^{-2} K^{-1}
Heavy wall	Vertical walls	0.40	622.92
	Roof	0.35	395.28
	Floor	0.42	320.65
Lite wall	Vertical walls	0.40	39.47
	Roof	0.35	298.58
	Floor	0.42	320.65

On the other hand, all dynamic models tested in the present work shows similar results: in particular, the average deviations between BEPS and TRNSYS are about 6.7 % and 5.0 % for heating and cooling calculations respectively. Moreover, the deviation between BEPS and EnergyPlus are about 4.6 % for heating calculations while the results provided by Energy Plus in cooling conditions present a weak deviation respect to other two models.

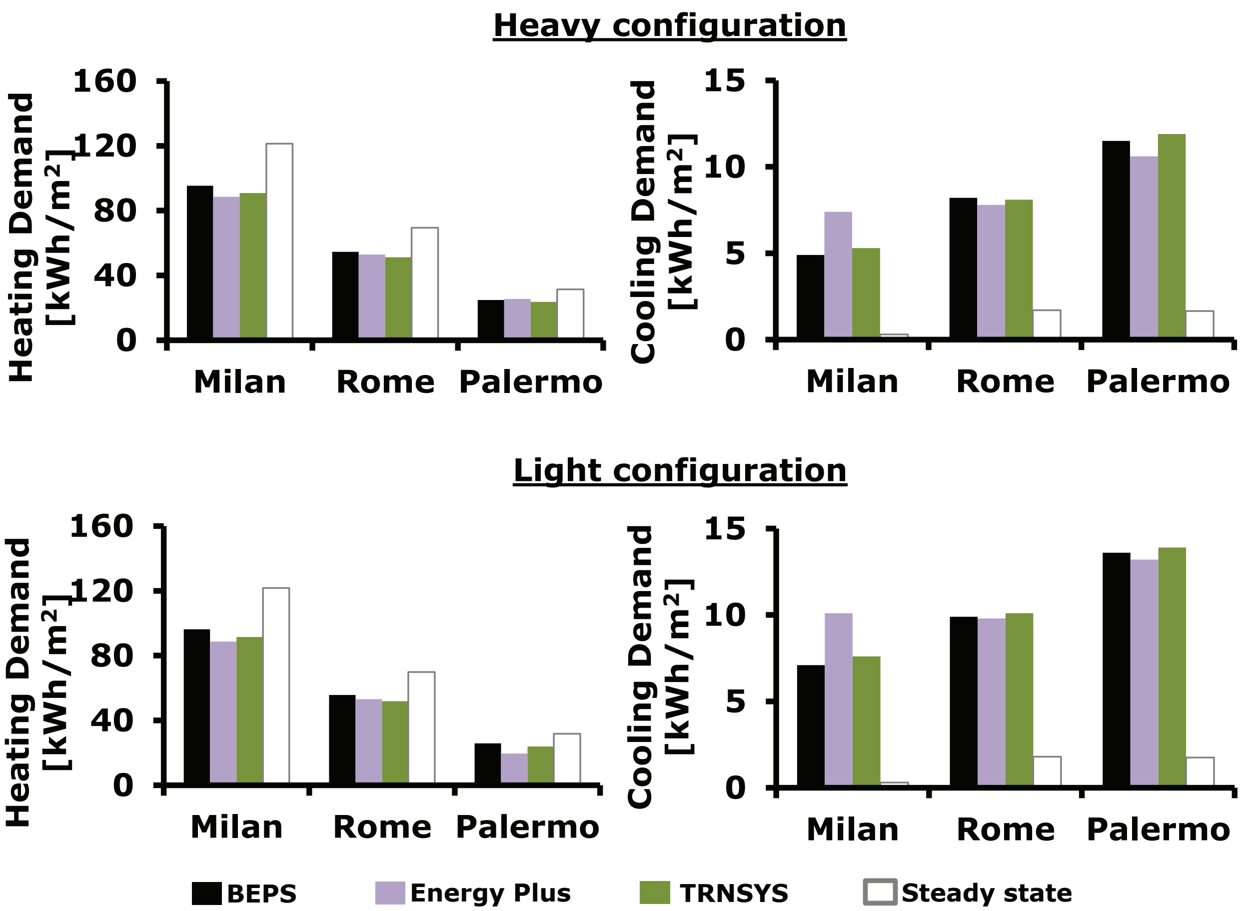

Fig. 10. Comparison between steady state and dynamic models for different building inertia conditions

These deviations are mainly due to the different discretizations of the internal environment and, in particular, to the calculation of the internal gains due to the solar radiation coming from the windows.

Starting from these results it is possible to perform sensitive analyses on the main parameters in the building design. As for instance, it is possible to analyze dynamically the effects obtained thank to the installation of a proper insulation in the building envelope. A question is generally remarkable: where is it convenient to put the insulation layer in an existing building?

Generally, the insulation on the internal side of the walls forces a strong coupling of the wall with the external environment ("cold wall condition") whereas in the case of external insulation the wall is coupled with the internal environment ("warm wall condition") [28]. In the first case, the thermal inertia effect of the building envelope is lost reducing the time-constant of the whole system with a consequent higher number of ON-OFF cycles of the heating/cooling system. On the other hand, in the "warm wall condition" the envelope acts as a source of heat compensating locally the variation of the external conditions and reducing the number of working hours of the heating/cooling system. Obviously, the choice between these two configurations depends strictly on the building configuration — especially if we consider that adding an internal layer has the effect to reduce the internal environment (which is not often possible) — and on an economic perspective.

Starting from the above considerations, several analyses have been conducted in order to analyze the effects of adding a new insulation layer on the benchmark building for both "cold" and "warm" configurations. The main assumption was to consider the maximum thickness which can be added without compromising the internal environment (in a geometric sense for the "cold configuration") and without increase overly the total wall thickness (this condition affects mainly the "warm wall configuration").

Fig. 11 reports the results obtained performing simulating the benchmark building with different insulations for several climatic conditions in Europe. As it is possible to see, the effects of the two insulation criteria are very different for this particular building: the internal insulation benefits are reduced respect to the external insulation case due to the limited insulation thickness which can be used. It is important to highlight that these results represent an example of a comparison between the two configurations in terms of energy consumptions without any investment analyses and, obviously, different building geometries could provide different results.

the maximum insulation thickness which can be installed and considering a reduction percent 100 % (the maximum case), 75 % and 50 %. The same considerations have

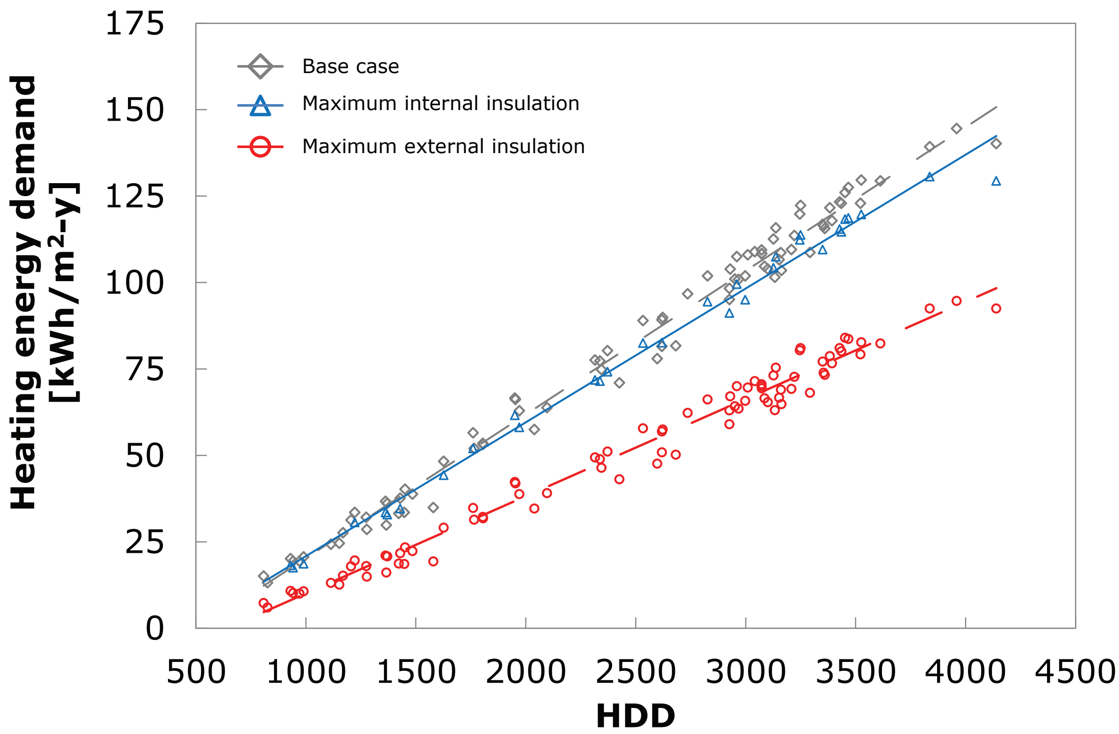

Fig. 11. Effects of maximum internal and external insulations available for the benchmark building in terms of yearly heating energy demand from BEPS

Extending the analyses to different insulation thickness, it is possible to analyze the impact of the increase in external and internal thermal resistances (by adding an insulation layer) on the heating energy consumption as function of HDD. Three values of external insulation thickness are selected starting from been adopted for the internal insulation calculations, but limiting the cases to only two values — 100 % (the maximum insulation thickness) and 75 %, due to the minimum thickness of insulation panels available.

The results, showed in Fig. 12, highlighted that the energy saved trend against HDD of both configuration,

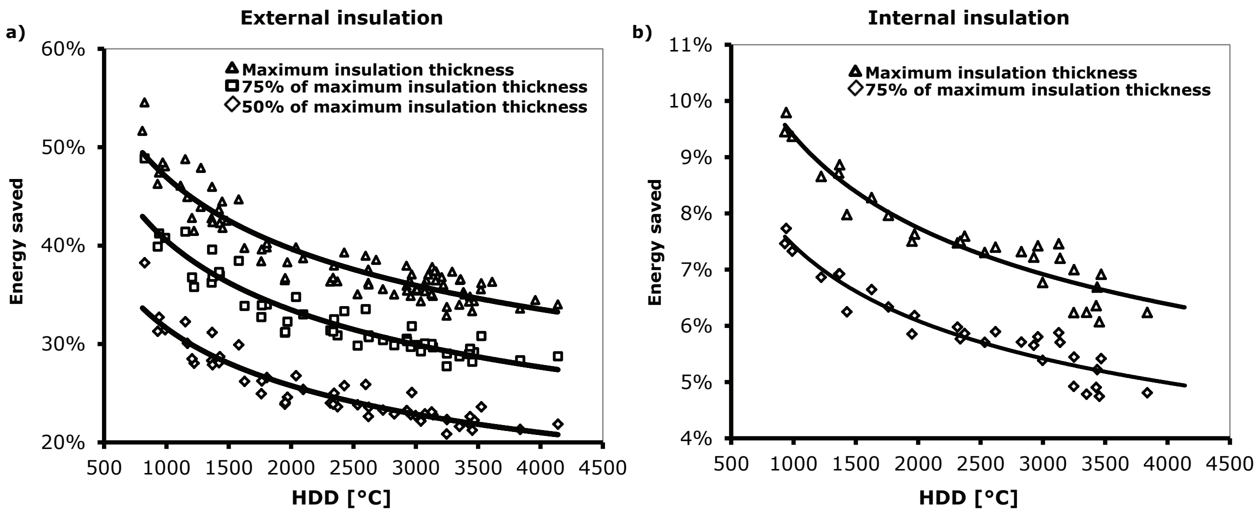

Fig. 12. Impact of introducing a proper insulation in the (a) external and in the (b) internal layers as function of HDD. Results provided by BEPS [28]

external (Fig. 12a) and internal (Fig. 12b). As expected, a decrease in the heating energy consumptions occurs for both conditions with greater values in the external installation, confirming the previous results. Moreover, it can be pointed out that the relative impact is stronger in warm climates (low HDD), due to the lower external temperature which reduces the relative efficacy of the insulation layer. It is important to highlight the term "relative" because this consideration is valid only in terms of percent respect to the previous configuration, whereas in absolute terms the energy saving obtained by using insulation in cold climates are generally higher, allowing better results in terms of economic investments. Finally, the dynamic effects are clearly highlighted by the nonlinear profile of the fitting curve in both configurations.

5. Conclusions

The present paper summarized the recent results obtained in modeling the building system with a special focus on the importance of numerical models used to estimate the energy consumptions. Both steady-state and dynamic models are investigated analyzing their main assumptions, limitations and fields of usage.

Generally, the steady state models are usually used to perform preliminary energetic assessments, essentially related to the renovation of existent buildings, and to preliminary design stage for new constructions, thanks to their fast calculations. Degree days method represents the simplest model and it is based on the assumption that the building energy demand is linearly dependent on the temperature difference between the internal and the external environment. Several methods are available to calculate DDs and a comparison between them showed that all models are able to predict correctly DDs if the difference between the base temperature and the mean monthly temperature is relevant.

Steady state models are also implemented in the common standards for the calculation of the building energy consumption. Comparing this approach with a dynamic one (BEPS) showed that neglecting the inertia effects (or using parameters to reproduce them) and the use of monthly averaged climatic data could provide incorrect results in terms of yearly energy demand, especially in cooling seasons when dynamic effects are stronger.

Therefore, the use of dynamic models are highly suggested, especially when different building configuration are investigated (as e.g. in the design stage or for a renovation perspective). In the present work, a sensitive analysis on the installation of a proper insulation in the building envelope is performed. In particular, the effects of adding a new insulation layer on the internal (cold wall configuration) and external (warm wall configuration) sides of the benchmark building were analyzed. The results showed very different influences effects of the two installation criteria: the internal insulation benefits are lower than the external insulation case due to the limited insulation thickness which can be used.

Finally, the impact of the increase in external and internal insulation layer on the heating energy consumption as function of HDD was investigated. Obviously, a decrease in the heating energy consumptions occur for both conditions, with greater values in the external installation (as already said), and, the relative impact of the insulation is stronger in warm climates (low HDD) for both configuration, due to the lower external temperature which reduces the relative efficacy of the insulation layer. Moreover, the dynamic effects are clearly highlighted by the nonlinear profile of the fitting curve in both configurations.

References

1. *Europe's buildings under the microscope*. Brussels, Buildings Performance Institute Europe (BPIE), 2011.

2. Isaac M., van Vuuren D. P. Modeling global residential sector energy demand for heating and air conditioning in the context of climate change. *Energy Policy*, 2009, vol. 37, pp. 507–21.

3. Wan K. K. W., Li D. H. W., Lam J. C. Assessment of climate change impact on building energy use and mitigation measures in subtropical climates. *Energy*, 2011, vol. 36, pp. 1404–1414.

4. EU. On the energy performance of buildings. Directive 2002/91/EC of the European Parliament and of the Council. *Official Journal of the European Communities*, 2002, pp. 65–71.

5. *CIBSE, Degree-days: Theory and Application. TM41.* London, Chartered Institution of Building Services Engineering, 2006. 106 p.

6. *ASHRAE Standard 90A-1980. Energy conservation in new building design*. Atlanta, American Society of Heating Refrigerating and Air Conditioning Engineers, 1980.

7. UNI EN ISO 13790:2008. Energy performance of buildings — Calculation of energy use for space heating and cooling. 2008. 162 p.

8. Ghiaus C., Allard F. Potential for free-cooling by ventilation. *Solar Energy*, 2006, vol. 80, pp. 402–413.

9. Baetens R., Jelle B. P., Gustavsen A. Phase change materials for building applications: A state-of-the-art review. *Energy and Buildings*, 2010, vol. 42, pp. 1361–1368.

10. Tagliafico L., Scarpa F., De Rosa M. Dynamic thermal models and CFD analysis for flat-plate thermal solar collectors — A review. *Renewable & Sustainable Energy Reviews*, 2014, vol. 30, pp. 526–537.

11. De Rosa M., Bianco V., Scarpa F., Tagliafico L. A. Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach. *Applied Energy*, 2014, vol. 128, pp. 217–229.

12. Hitchin E. R. Degree-days in Britain. *Building Service Engineering Research and Technology*, 1981, vol. 2, pp. 73–82.

13. *ASHRAE Handbook: Fundamentals*. Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2009.

14. Hitchin E. R. Developments in Degree-Day Methods of Estimating Energy Use. *Building and Environment*, 1990, vol. 25, pp. 1–6.

15. Schoenau G. J., Kehrig R. A. A method for calculating degree-days to any base temperature. *Energy and Buildings*, 1980, vol. 14, pp. 299–302.

16. De Rosa M., Bianco V., Scarpa F., Tagliafico L. A. Historical trends and current state of heating and cooling degree days in Italy. *Energy Conversion and Management*, 2015, vol. 90, pp. 323–335.

17. Thom H. C. S. Seasonal degree-day statistics for the United States. *Monthly Weather Reviews*, 1952, vol. 80, issue 9, pp. 143–147.

18. Directive 2010/31/EU of the European Parliament and of the Council on the Energy Performance of Buildings. L153/13. 2010. Available at: http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ: L:2010:153:0013:0035:EN: PDF (accessed: 24.03.2015).

19. Directive 2012/27/EU of the European Parliament and of the Council on the Energy Efficiency. L315/1. 2012. Available at: http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32012L0027&from=EN (accessed: 24.03.2015).

20. Boyer H., Brau J., Chabriat J. P., Grondin-Perez B., Tourrand C. Thermal building simulation and computer generation of nodal models. *Building and Environment*, 1996, vol. 31, pp. 207–214.

21. Nielsen T. R. Simple tool to evaluate energy demand and indoor environment in the early stages of building design. *Solar Energy*, 2005, vol. 78, pp. 73–83.

22. Eiker U. *Solar Technologies for Buildings*. Chichester, John Wiley and Sons, 2003.

23. Yazdanian M., Kelms J. H., Measurement of the Exterior Convective Film Coefficient for Windows in Low-Rise Buildings. *ASHRAE Transactions*, 1994, vol. 100, pp. 1087–1096.

24. Booten C., Kruis N., Christensen C. *Identifying and Resolving Issues in EnergyPlus and DOE-2 Window Heat Transfer Calculations*. National Renewable Energy Laboratory, Golden CO (USA), 2012. Technical Report NREL/TP-5500–55787.

25. Palyvos J. A. A survey of wind convection coefficient correlations for building envelope energy systems' modeling. *Applied Thermal Engineering*, 2008, vol. 28, pp. 801–808.

26. Nicol K. The energy balance of an exterior window surface, Inuvik, N. W.T., Canada. *Building and Environment*, 1977, vol. 12, pp. 215–219.

27. Perez R., Ineichen P., Seals R., Michalsky J., Stewart R. Modeling daylight availability and irradiance components from direct and global irradiance. *Solar Energy*, 1990, vol. 44, pp. 271–289.

28. Bianco V., De Rosa M., Scarpa F., Tagliafico L. A. Analysis of energy demand in residential buildings for different climates by means of dynamic simulation. *International Journal of Ambient Energy*, 2014. DOI: 10.1080/01430750.2014.907207